Probing Minimal Supersymmetry at the LHC with the Higgs Boson Masses

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ATLAS and CMS report indications of a Higgs boson at $M_h \sim 125$ GeV. In addition, CMS data show a tenuous bump in the ZZ channel, at about 320 GeV. We make the bold assumption that it might be the indication of a secondary line corresponding to the heaviest scalar Higgs boson of Minimal Supersymmetry, H, and discuss the viability of this hypothesis. We discuss also the case of a heavier H, the relevance of the $b\bar{b}$ decay channel is underlined.

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Introduction. Indications of a Higgs boson around a mass:

$$M_h \simeq 125 \text{ GeV} \tag{1}$$

have been presented by the ATLAS [1] and CMS [2] collaborations in the reactions:

$$p + p \to h + \text{ All} \to \gamma\gamma + \text{ All} \tag{2}$$

$$p + p \to h + \text{ All} \to ZZ + \text{All}; \quad ZZ \to 4 \text{ charged leptons} \tag{3}$$

observed at the LHC at c.o.m. energy: $\sqrt{s} = 7$ TeV.

The value of the mass, should it be confirmed, is interesting by itself, in that it is compatible with the restrictions posed by the Minimal Supersymmetric Standard Model [3] [4], MSSM in short. It is well known that the tree level inequality for the mass of the lightest Higgs boson:

$$M_h^2 \leq \cos^2(2\beta) M_Z^2 \text{ (tree level)} \tag{4}$$

receives radiative corrections, due to the exchange of the top quark and its two scalar partners, $\tilde{t}_{L,R}$, which may bring the mass up to $M_h \sim 135$ GeV, for "reasonable" values of the scalar partner masses. Encouraged by this fact, we have investigated the consequences of the next simple prediction of MSSM, namely that there must be two Higgs doublets, one coupled to *up* and the other to *down* fermions.

The introduction of a singlet superfield [5] [6] leads to the Next-to-Minimal Superymmetric Standard Model (NMSSM), which modifies the tree level inequality (4) thereby reducing the role of the radiative corrections and allowing for lighter scalar top quark partners and better naturalness [7]. However, predictivity in NMSSM is greatly reduced for what concerns the properties of the scalar Higgs particles and we think it wise to stick to the minimal option unless some real contradiction with data is found.

The mass-matrix of the two, CP-even, Higgs particles of the MSSM, h and H (with h the lightest), depends upon four parameters: the VEV ratio, parametrized in terms of an angle β, the masses of the Z boson and of the CP-odd Higgs boson, A, and the average mass of the top scalar partners, which appears in the radiative correction mentioned above. Here, we take the usual notation:

$$\langle 0|H_u^0|0\rangle = v \sin\beta; \quad \langle 0|H_d^0|0\rangle = v\cos\beta; \quad 0 < \tan\beta < +\infty \tag{5}$$

$$v^2 = (2\sqrt{2}G_F)^{-1} = (174 \text{ GeV})^2 \tag{6}$$

Diagonalizing the mass matrix, we obtain two eigenvectors which express the physical Higgs fields in terms of $H_{d,u}^0$ and determine the coupling of h and H to quarks, leptons and gauge bosons [8] [9].

Assume now the mass in (1) and assume that we know the other mass, M_H, as well. We can express everything in terms of $M_{Z,h,H}$ and remain with one unknown parameter only, namely $\tan\beta$. We can derive all the observable quantities, such as the ratios of $\sigma \times BR$ in the MSSM to the one in the SM for the channels observed in (2) and (3), and see (i) how the level of observation of the 125 GeV signal compares to the SM; (ii) what is the visibility level of H in channels (2) and (3), and (iii) which are the best suited channels for the observation of H. In addition, we may determine, always in terms of $\tan\beta$, the mass value of the CP-odd boson, A, and the mass scale of the top scalar partners.

The total production cross section for the Higgs particles is dominated by gluon-gluon fusion, which in turn is dominated by the top quark loop. However, CMS searches also for $\gamma\gamma$ events in the central region, accompanied

by two, clean, backward and forward hadron jets. In these conditions, vector boson fusion is dominant. The ATLAS analysis enhances vector boson fusion as well.

Results. In the numerical calculations, we take as a guiding values for M_H:

- the value $M_H = 320$ GeV, in correspondence to which an "excess" can be seen in CMS data, albeit with small significance at about 1/3 with respect to SM [10];
- the value $M_H = 500$ GeV, to exemplify the behavior above the $t\bar{t}$ threshold.

Results are summarized in Figs. 1 to 6. The shaded areas in the figures indicate the regions where the $(\sin\beta)^{-1}$ and $(\cos\beta)^{-1}$ factors make the Yukawa couplings of t and b quarks so large as to run out of the perturbative region before the GUT scale is reached [11].

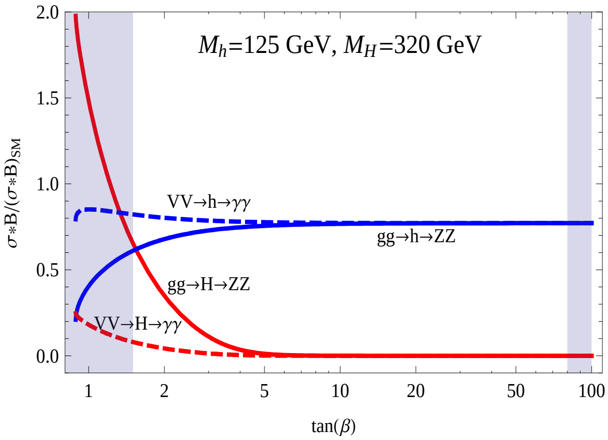

FIG. 1: Values of $\frac{\sigma\times BR}{(\sigma\times BR)^{\rm SM}}$ in the ZZ and $\gamma\gamma$ channels for h, $M_h = 125$ GeV, and H, $M_H = 320$ GeV. Gluon-gluon fusion is assumed for ZZ and vector boson fusion for $\gamma\gamma$.

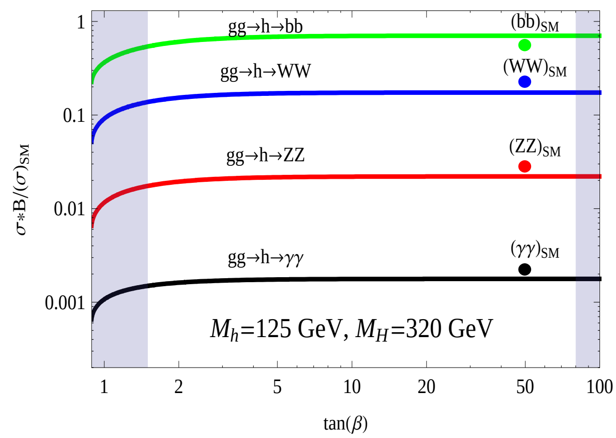

FIG. 2: Values of $\frac{\sigma\times BR}{\sigma^{\rm SM}}$ for h, $M_h = 125$ GeV and $M_H = 320$. For comparison, visibilities of the different channels in SM are shown by the dots in the right hand corner.

We find that, for $M_H = 320$ GeV, the light Higgs boson h behaves rather closely like the SM Higgs boson, in both ZZ and $\gamma\gamma$ channels, Fig. 1. For $M_H = 500$ GeV the decoupling limit is reached and h is essentially an SM Higgs boson. We adopt the gluon-gluon fusion mechanism for the ZZ channel and assume vector boson fusion for $\gamma\gamma$. A positive interference of the two production mechanisms when initiated by quarks, may produce values of the ratio $\sigma\times BR$ in SUSY vs. SM larger than unity.

We show in Fig. 2 the values of $\frac{\sigma\times BR}{\sigma^{SM}}$ for SUSY h, $M_h = 125$ GeV and $M_H = 320$ GeV. The value of $\sigma\times BR$ is obtained by multiplying by the SM cross section for a Higgs boson of the same mass (~ 10 pb). For comparison, visibilities of the different channels in SM are shown by the dots in the right hand corner. The $b\bar{b}$ branching ratio is ~ 1.5 larger than the SM one, due to the factor $(\cos\beta)^{-1}$ in the Yukawa coupling.

For H, the vector boson fusion $VV \to H \to ZZ$ gives a negligible result and we are left with gg fusion as the production mechanism. Not surprisingly, a large difference is made by being below or above the top quark threshold.

For $M_H = 320$ GeV, the ratio of $\sigma\times BR(H\to ZZ)$ in SUSY over the same in SM drops very fast at the increase of $\tan\beta$, Fig. 1. In a window around $\tan\beta = 2$, H would appear as a subdominant companion of h in VV and, to a minor extent, in $\gamma\gamma$ channels. For $\tan\beta \geq 4$, the VV decay branching ratio drops and the $b\bar{b}$ channel takes over, due to the $(\cos\beta)^{-1}$ factor, Fig. 3.

Taking seriously the bump at $M_H = 320$ GeV, we get from Fig. 1:

$$\frac{\sigma\times BR(H\to ZZ)^{\rm MSSM}}{(\sigma\times BR)^{\rm SM}} \sim 0.3 \quad \text{at} \quad \tan\beta \sim 2 \tag{7}$$

and, in correspondence, see also Figs. 5 and 6:

$$\frac{\sigma\times BR(h\to\gamma\gamma)^{\rm MSSM}}{(\sigma\times BR)^{\rm SM}} \sim 0.8; \; \frac{\sigma\times BR(H\to\gamma\gamma)^{\rm MSSM}}{(\sigma\times BR)^{\rm SM}} \sim 0.04 \tag{8}$$

$$M_A = 310 \text{ GeV}; \; \sqrt{M_{\tilde{t}_R} M_{\tilde{t}_L}} = 3.9 \text{ TeV} \tag{9}$$

For $M_H = 500$ GeV, the $t\bar{t}$ channel is dominating until $\tan\beta \sim 5$ and the visibility of H is related to the ability to detect top quarks. For larger values of $\tan\beta$ the $b\bar{b}$ channel takes over. We compare the visibility of the different channels for H below and above threshold in Figs. 3 and 4. Absolute values of $\sigma \times BR$ are again obtained by multiplying by the SM cross section for a Higgs boson of the corresponding mass.

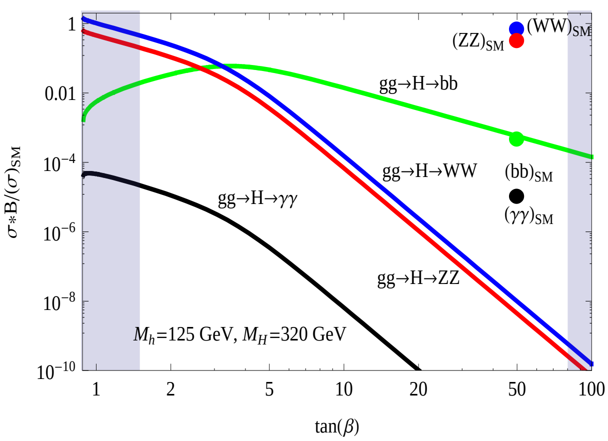

FIG. 3: Values of $\frac{\sigma \times BR}{\sigma^{SM}}$ for H, $M_H = 320$ GeV. SM values shown in the right corner.

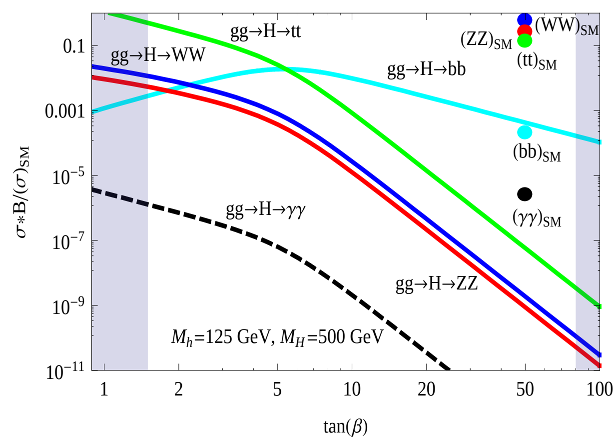

FIG. 4: Values of $\frac{\sigma \times BR}{\sigma^{SM}}$ for H, $M_H = 500$ GeV. SM values shown in the right corner.

Details of the calculation. In the basis (H_d, H_u), the mass matrix of the CP-even Higgs fields is given by:

$$\mathcal{M}_S^2 = M_Z^2 \begin{pmatrix} \cos^2\beta & -\cos\beta\sin\beta \\ -\cos\beta\sin\beta & \sin^2\beta \end{pmatrix} + M_A^2 \begin{pmatrix} \sin^2\beta & -\cos\beta\sin\beta \\ -\cos\beta\sin\beta & \cos^2\beta \end{pmatrix} + \begin{pmatrix} 0 & 0 \\ 0 & \delta \end{pmatrix} \tag{10}$$

with δ the radiative correction:

$$\delta = \frac{3\sqrt{2}}{\pi^2 \sin^2\beta} G_F (M_t)^4 t; \quad t = \log\left(\frac{\sqrt{M_{\tilde{t}_R} M_{\tilde{t}_L}}}{M_t}\right)$$

The first term in $\mathcal{M}_S^2$ arises from the so-called Fayet-Iliopoulos term [12] determined by the gauge interaction. In the radiative corrections we have kept only the top-stop contribution which is by far the dominating one.

We eliminate M_A^2 equating the trace of $\mathcal{M}_S^2$ to the sum of the eigenvalues, $M_h^2 + M_H^2$, and obtain t as a function of $\tan\beta$ from the difference. One obtains two real solutions:

$$t = F^{(\pm)}(\tan\beta) \tag{11}$$

only for

$$\tan\beta \geq 0.89 \tag{12}$$

which therefore provides an absolute lower bound, roughly compatible with the border of the shaded exclusion region.

The function in (11) is plotted versus $\sin\beta$ in Fig. 5 for the two guiding values of M_H. The solid (dotted) lines correspond to $F^{(-)}$ ($F^{(+)}$). We shall choose $F^{(-)}$, which minimizes the size of the radiative correction. In correspondence, we plot in Fig. 6 the values of M_A^2, solid (dotted) lines referring to the solid (dotted) line solution in Fig. 5.

Substituting this function back into (10), we compute the two eigenvectors:

$$\begin{aligned} \mathbf{S}_h(\tan\beta) &= (S_{hd}, S_{hu}) \\ \mathbf{S}_H(\tan\beta) &= (S_{Hd}, S_{Hu}) \end{aligned} \tag{13}$$

with the physical fields given by:

$$h = S_{hi} H_i \quad H = S_{Hi} H_i \quad (i = d, u) \tag{14}$$

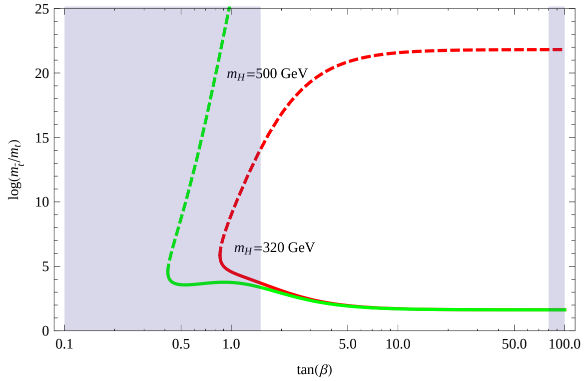

FIG. 5: Solutions of eq. (11) vs. $\tan\beta$ for the values of M_H considered in the text.

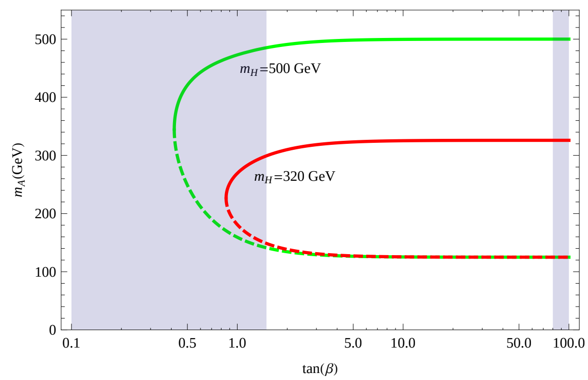

FIG. 6: Values of the axial meson mass vs. $\tan\beta$ or the values of M_H considered in the text.

Couplings of h and H to exclusive channels, e.g. WW, $t\bar{t}$, etc., are given by the SM coupling multiplied by factors which depend upon the components of the eigenvectors in (13) and β, see Tab. I. The two components of $\mathbf{S}_h$ are positive and about equal for $\tan\beta \sim 2$ while the components of $\mathbf{S}_H$ have opposite sign, which considerably suppresses the coupling of H to the VV channels.

Ratios of production cross sections to the SM ones can now be computed upon specifying the dominant mechanism:

$$\begin{aligned} R_{gg}(h) &= \frac{\sigma(gg \to h)^{\rm MSSM}}{\sigma(gg \to h)^{\rm SM}} = \frac{S_{hu}^2}{\sin^2\beta} \\ R_{\rm VBF}(h) &= \frac{\sigma(VV \to h)^{\rm MSSM}}{\sigma(VV \to h)^{\rm SM}} = (\cos\beta\; S_{hd} + \sin\beta\; S_{hu})^2 \end{aligned} \tag{15}$$

and similarly for H.

To determine the decay rates, we have used the program HDECAY [13] which gives the decay rates of the SM Higgs boson in exclusive decays, and have multiplied them by the appropriate factors taken from Tab. I.

	$WW = ZZ$	$t\bar{t} = c\bar{c}$	$b\bar{b} = \tau^+\tau^-$
h	$\cos\beta\; S_{hd} + \sin\beta\; S_{hu}$	$(\sin\beta)^{-1} S_{hu}$	$(\cos\beta)^{-1} S_{hd}$
H	$\cos\beta\; S_{Hd} + \sin\beta\; S_{Hu}$	$(\sin\beta)^{-1} S_{Hu}$	$(\cos\beta)^{-1} S_{Hd}$

TABLE I: Ratios of the couplings of h and H to the SM Higgs boson couplings, for different exclusive channels.

The decay rates in $\gamma\gamma$ are dominated by WW and $t\bar{t}$ loops. We take from Ref. [14] the SM loop amplitudes and rescale them with the appropriate couplings given in the previous Table.

Conclusions. A clear prediction of Supersymmetry is the presence of two Higgs field doublets, one coupled to u and the other to d quarks. If the 125 GeV signal is confirmed, the next thing to look for is the presence of a secondary line, in VV, $\gamma\gamma$ and $b\bar{b}$. We have shown that these signals are viable for M_H below the $t\bar{t}$ threshold, in different regions of $\tan\beta$. An H at 320 GeV in ZZ would fit very well into MSSM and this calls for close scrutiny of this region. Above threshold, one needs to control the $t\bar{t}$ and, for $\tan\beta > 4$, the $b\bar{b}$ signals.

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